MONTHLY WEATHER REVIEW

Editor, W. J. HUMPHREYS

VOL. 62, No. 4
W.B. No. 1128

APRIL 1934

CLOSED June 2, 1934
Issued July 23, 1934

RECENT ADVANCES IN ANEMOMETRY [1]

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[Weather Bureau, Washington, May 1934]

Quite important advances have been made in the theory and the practical development of the cup anemometer within the past 2 years.

On the theoretical side this progress consisted chiefly in measuring all the fundamental aerodynamic forces on various forms and sizes of cups, singly and in combination, under as wide a range as practicable of cup wheel sizes and values of Reynold's number. A research project of this character for the Weather Bureau is still in progress at Langley Field by the National Advisory Committee for Aeronautics. When all the observational data are available it is believed they will be of great value in the development of really useful aerodynamic relationships between wind velocity and some measure of the angular velocity of the cups, such as the revolutions per minute, or cup turns per unit wind travel.

Purpose of this note.—My principal objects in this brief paper are: (1) to advocate certain simple and exact methods of testing rotation anemometers; (2) to plead for the publication of *original observations* by others who test anemometers; and (3) to present in general terms the systematic characteristics of the performances of cup anemometers, illustrated by results from recent tests.

Every investigator owes it to himself, and to the cause of science, to present his original observations as fully as possible, and to retain an adequate number of digits in the numerical values which constitute the basic test.

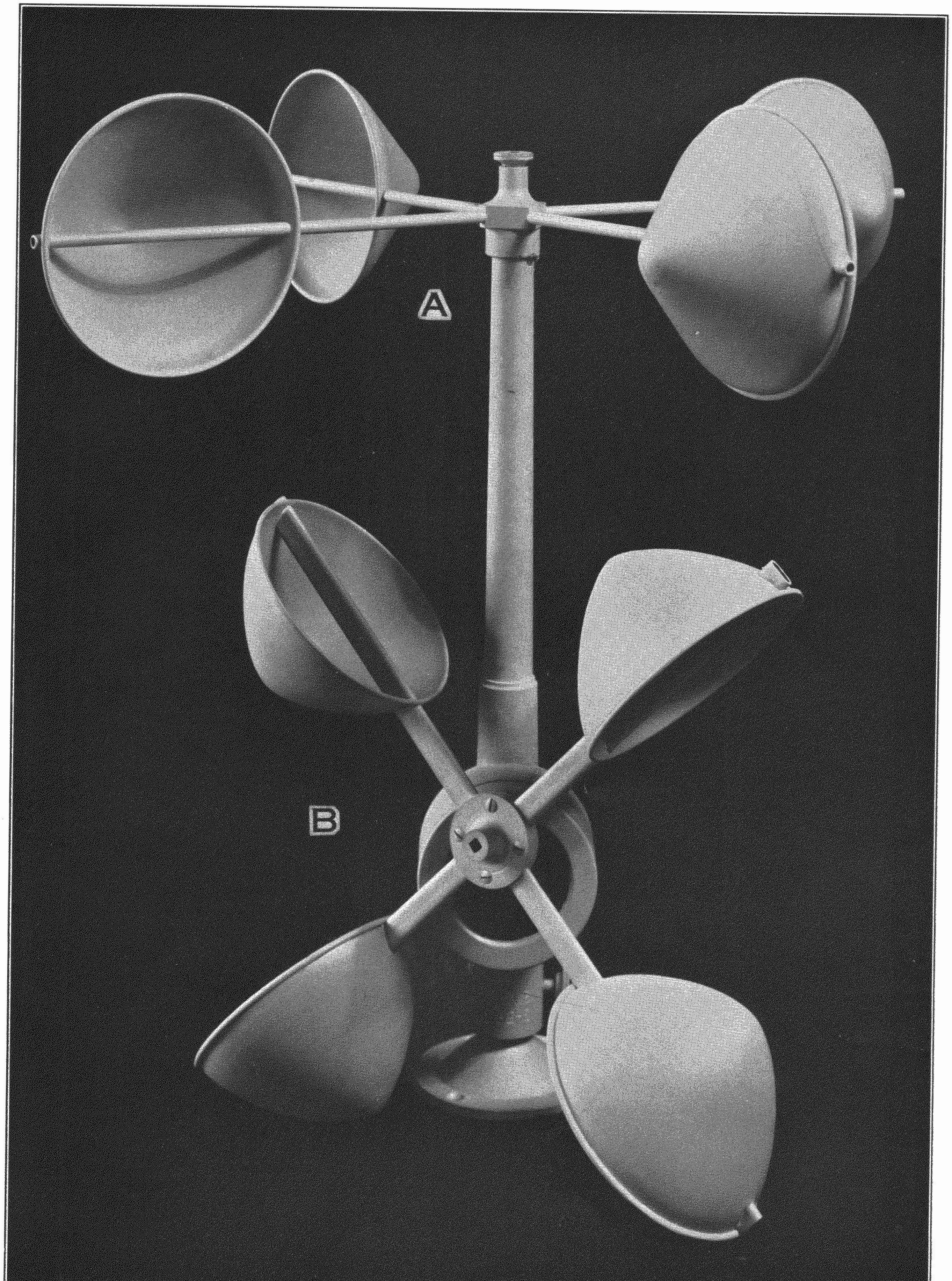
I must deplore a prevailing tendency of withholding original observations and presenting only arbitrarily "smoothed" and "adjusted" values rounded out to a scale of whole velocity units. In the interest of final accuracy in the analysis of test data the decimal place of "hundredths" should be retained in both the true and the indicated wind velocity, particularly for moderate or low values, and especially when the velocity unit is meters per second, which is really a very large and coarse unit. I do not pretend to claim that hundredths of meters per second or hundredths of miles per hour are accurately shown in ordinary test data at a particular velocity nevertheless their retention is a valuable aid to the computor, whose task is one of segregating the inevitable errors of observation from the small and obscure, but important, systematic characteristics of test data and definitely evaluating those characteristics. The writer who withholds original observational data and needlessly discards useful fractional values in anemometer tests is guilty of rejecting the most informative portion of his data and passing on to other students values that exaggerate the errors of observation and obscure the systematic performance features of the instruments. Any good cup anemometer is highly dependable in its action and fully justifies refinements in testing it.

Sound-testing technique.—There are, of course, good and poor ways of testing the performance of any rotation anemometer. Nearly all cup anemometers as now made for daily use are already provided with electrical contact makers which actuate a buzzer, or which may be used to make a chronographic record. Each buzz or registration then represents a certain exact number of cup turns, which varies widely in different instruments and ranges from 8 and a fraction to 500 or more.

These available provisions are entirely adequate, for all ordinary purposes. Other special provisions are more or less fanciful or superfluous. For practical tests I regard audible contacts and counting facilities for every 64 cup turns as all-around adequate. A test at a definite uniform velocity, W, consists simply in measuring accurately, by means of a good stop watch, the whole number of electrical contacts, C, in an elapsed time, t seconds. Chronographic registration, in my mind, is quite superfluous, or even objectionable, especialy because it generally requires quite special equipment, with fast moving paper feed and some one, from such record sheets, must later count out the actual number of registrations made and ascertain the elapsed time in seconds. In reality these essential data are more promptly, more easily, and just as accurately secured at the time of the test by the use of a stop watch and the counting of audible contacts. If each contact counted represents, say n cup turns, then R, the number of cup turns per minute, $=60nC \div t$.

I cannot emphasize too strongly, that for anemometer tests, all original observations consist essentially of W, the true speed of the wind in the tunnel, C the number of contacts counted, and t the elapsed time in seconds. Out of these we calculate R. This derived basic datum, R, the cup revolutions per minute, is a perfectly definite and exact index of the behavior of the particular cup wheel tested at the corresponding velocity, W. We also have another equally fundamental datum or index of cup behavior, namely, N, the number of cup wheel turns per mile or other unit of wind travel. Both R and N are numerical magnitudes for each particular cup wheel which are wholly free from any kind of personal assumptions such as are involved when we employ the familiar concept "indicated velocity." In these cases we must

[1] Paper presented at the April 1934 meeting of the American Meteorological Society, Washington, D.C.



Cup-wheel anemometers: A, No. 24 in the tables, with 90° cone backs and medium beaded edges; B, new form of beaded cup wheel with hollow, elliptical arms.

say, for example, each turn of the cups represents say 2.5 meters of wind travel, or that 500 cup turns represent a mile. Both assertions are erroneous except possibly for some one particular velocity which can not be known a priori. Nevertheless, the datum, "indicated velocity, V", is very useful in its proper place.

Fortunately these basic data R, N, and V are rigorously related by very simple equations, which for English units are:

$$NW = 60R = AV = \text{Cup wheel turns per hour} \qquad (1)$$

In the last term, A is the so-called "gear train number", or the assumed number of cup wheel turns per indicated mile of wind travel.

Each datum N, R, and V is directly derivable from the basic test data by the following rigorous equations:

$$N = \frac{3600nC}{tW} \qquad (2)$$

$$R = \frac{60nC}{t} \qquad (3)$$

$$V = \frac{3600nC}{tA} \qquad (4)$$

In the last term the ratio $\frac{n}{A}$ is generally a simple fraction like $\frac{1}{30}$, $\frac{1}{60}$, etc.

Group means.—The formation of group means of numerous individual observations derived from different tests and at irregular spacing of conditions is necessary in practically all classes of data, not only to lessen the inevitable errors of observation but also to reduce labor in the analytical processes of curve fitting, etc. Unless this is done with a careful regard for right and wrong methods the inherent accuracy of the original data will be reduced rather than preserved. The principle is illustrated in figure 2. Points a and b are assumed to be observations represented by the curved line passing near them. The ordinary arithmetical mean values of the two coordinates of a and b locate a new point c, which falls quite a bit off the curve depending upon the number of observations combined and how much the line is curved between the points. In the application of this idea to anemometer test data it will be remembered that, as shown in figure 1, values of R or V plotted against W form nearly straight lines throughout their entire range. It is best, therefore, to form group means of data between R or V and W. The corresponding values of other data, such as N, should then be computed from the R or V data by the use of the rigorous relations in equation 1.

The use of the foregoing rigorous equations and relations greatly facilitate the calculation of test data with the minimum of arithmetical inaccuracies.

Friction.—Actual measurements by stroboscopic methods of the energy dissipated by the friction of various forms of plain and ball bearings in anemometers have vastly clarified this heretofore rather obscure subject.

Friction, unless excessive, is of very minor importance at all wind velocities above 20 or 30 miles per hour. It is however, of great importance at all low velocities and should be reduced to the utmost in any instrument claiming to be a high standard.

This result, including high durability and freedom from frequent demands for lubrication can be secured only by the use of ball bearings. Four prerequisites must be satisfied:

(1) The bearings must be of the highest design and grade. Just any old ball bearing will not do.

(2) The entire load and lateral thrust is best carried on the top bearing.

(3) The cup wheel hub must be designed so that the plane of the cup wheel arms coincides exactly or nearly with the plane of the balls in the top bearing. When so arranged the lateral thrust and attendant friction at the bottom end of the spindle is mostly eliminated.

(4) The ball bearing at the bottom end of the spindle should be of small diameter and designed to carry lateral thrust only. A small plain bearing such as now in use, but without the steel step, is quite sufficient.

Every cup wheel remains stationary for certain very feeble winds. It is difficult to evaluate the exact low velocity, W_0, which is just adequate to keep the cups turning. My best evaluation of W_0 for the new instrument now in experimental use is about 0.3 mile per hour. The new forms of cup wheel will just turn very slowly in this wind.

In a few types, such for example as the heated anemometer which furnished such a remarkable record of superhurricane winds at Mount Washington April 11 to 12, 1934, the instrument simply fails to run at low and moderate velocities because of relatively large frictional effects. While these effects are unimportant at high wind velocities, nevertheless excessive friction always causes large scale corrections, generally affecting both low and high velocities. In other words, small-scale corrections over a wide range of velocities are impossible unless the friction is a minimum. The curvature of the anemometer law must also be a minimum.

Characteristics of cup wheel performance.—We now have numerous tests on several different 4-cup systems. Some of these were made in a rather ill-adapted vertical jet wind tunnel at the Daniel Guggenheim Airship Institute at Akron, Ohio, others at the Bureau of Standards, and still others at the Langley Memorial Laboratory of the National Advisory Committee for Aeronautics. While minor systematic differences of the order of 4 percent in extreme cases are shown in results from these different sources, the major characteristics of cup wheel performance stand out boldly in all. Furthermore, even though the test data available to me on 4-cup anemometers is far superior to and in excess of that on 3-cup wheels, and especially at higher velocities, nevertheless from the most critical study I can make I can find nothing magical or superior in 3-cup systems as a type. Both devices are actuated by the same general aerodynamic forces. Under conditions of use equally favorable to each, their performance cannot in the very nature of things differ except in quite unimportant details. This assertion will, I believe, be borne out by any analysis by rigorous methods of any original observations available.

If we plot R or V against W, all good anemometer tests, if very carefully examined, fall in a systematically curved line convex downward, cutting the axis of W at a definite value, W_0, fixed by the instrumental friction, see figure 1, which is not drawn to scale and exaggerates the effects. If actual good observations were plotted to scale in this diagram the first impression would be that the line is practically straight, and the inattentive student is quite prone to seize upon the straight line as an entirely adequate approximation to cup-wheel performance. The slight curvature is at first strong, thereafter the line asymptotically approaches a straight line. It will not do, however, to ignore the real systematic curvature. It will not do to substitute a straight line as an approximate representation for the anemometer law. Exactitude in anemometry requires that the curvature of this line be evaluated as best we can. The empirical method [2] developed by me for doing this has stood the test of quite severe usage, and especially adapts itself to the satisfactory representation of new and better observations than originally available. The ultimate solution of this problem of inherent curvature shown by all observations will of course be most completely attained by the analysis of the fundamental aerodynamic data now being gathered and studied. Pending this accomplishment we are finding, by empirical studies, not only how to evaluate the curvature best but especially how to design cup systems which show a minimum amount of curvature in performance.

If, instead of plotting R or V against W, we plot that other important index of cup wheel performance, namely,

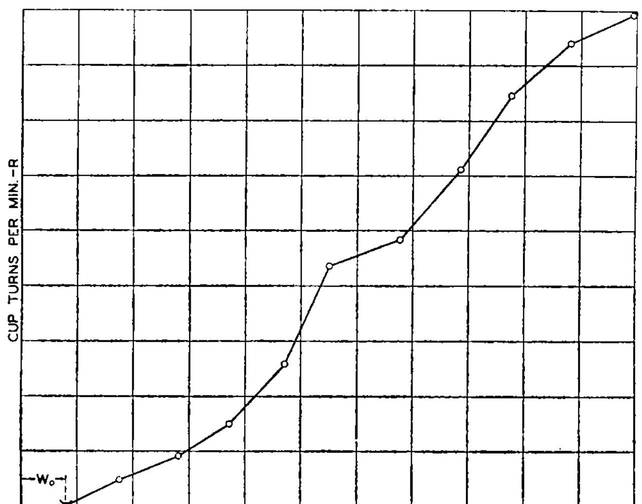


FIGURE 1.—Diagrammatic representation of the main characteristics between true wind velocity and cup turns per minute which are directly proportional to indicated velocity. The line starts at a point W_0, trends convex towards the axis of the true wind, with a small but important amount of curvature, becoming asymptotically straight.

N = cup turns per mile, we get a very strongly curved line shown diagrammatically, that is, not to scale, in figure 2. This line must of course cut the axis of W at the point W_0. The values of N rise rapidly and asymptotically approach a limiting high value. In a word, the curve shown by many sets of test values of N and W for anemometers possesses all the essential characteristics of the hyperbola when referred to coordinate axes parallel to its asymptotes. Numerous trials with very diverse test data now show that this empirical curve represents anemometer performance to an extent which is really quite remarkable. The form of the full equation for use with observations of N and W is:

$$f+Wb+Na+NW=0 \tag{5}$$

Since $NW=AV=60R$ similar equations for the analysis of test values of W and V or W and R are:

$$f'+Wb'+aV/W+V=0 \tag{6}$$

$$f''+Wb''+aR/W+R=0 \tag{7}$$

[2] A Rational Theory of the Cup Anemometer, Charles F. Marvin. MONTHLY WEATHER REVIEW, vol. 60, February 1932, pp. 43-57.

in which

$$f'A=60f''=f \text{ and } b'A=60b''=b \tag{8}$$

In the best ordinary anemometers the friction is very slight, and experience shows that it is best in such cases to replace the absolute term in each of the basic equations by a composite term bW_0 in which W_0, as already mentioned, is the wind just adequate to keep the cups in motion and which is evaluated by good judgment based on other than the ordinary test data. This course is necessary chiefly because it is difficult to make good tests at sufficiently low velocities to evaluate W_0 directly. All the equations then take on a simpler form with only two constants to be evaluated, thus

$$(W-W_0)b+Na+NW=0 \tag{9}$$

The corresponding equations for (6) and (7) are obvious.

The least-square calculation of the parameters of equation 5 is somewhat easier than for either of the other equations, but the numerical values, theoretically, should be identical by either of the equations in the absence of

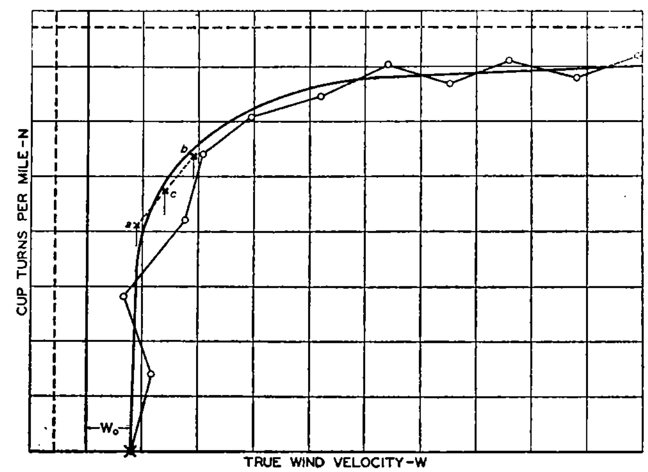


FIGURE 2.—Diagrammatic representation of the relation between true wind velocity and cup turns per mile. The characteristic features are those of the hyperbola referred to axes parallel to its asymptotes.

arithmetical inaccuracies. However, small differences necessarily arise because of inherent errors and irregularities in the observational data, and because the hyperbolic equation is only empirical and only imperfectly fits even the best observations. Parameters calculated from equation 5, moreover, have greater value because they are wholly free from any assumptions involved in the arbitrary number A which is required in all the V, W, relationships. Experience in these calculations indicates a strong advantage in favor of the use of the N, W, relationship. The rigorous equation 1 always easily permits any exact transformations desired.

The remarkable adaptability of the hyperbolic equation to the anemometer is the definite and specific significance of its constants. As already stated, W_0 represents the quite definitely known low wind velocity just adequate to keep the cups turning. We may continue to regard f, f', and f'' as friction terms even when large, because they change greatly in value as soon as the friction becomes large and causes the cups to stand still or move very slowly at low velocities.

The important constant a is exclusively a measure of the curvature in the V, W, or the R, W, relationship. This is clearly obvious from equations 6 and 7 because both become strictly straight or nearly straight lines when $a=0$ or is very small.

Finally, b, b', or b'' is a limitation or asymptotic value of the number of cup turns per mile in one case and in the other the limitation to which the ratio V/W or R/W approaches, that is, the limiting direction of the tangent to the line at very high velocities.

Whenever the friction is considerable all three parameters of the hyperbolic equation must be evaluated from the test data if we are to secure a good fit to the observations of either N or V. When f or f' becomes large it also takes on the negative sign and the resulting

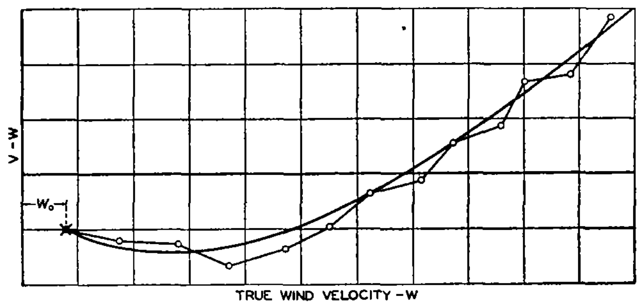


FIGURE 3.—Form of diagram to give a graphic representation of the inherent curvature of the relations between W and V, and also to visualize the relatively small conflicts and inconsistencies of observational data.

equation then fails to represent low velocities in a rational manner. A notable case of this kind has been found in computing test data for the heated anemometer no. 2, which gave the very remarkable record of superhurricane winds on Mount Washington, N.H., during the entire 24 hours April 11 to 12, 1934. The tests ranged from 12 to 143 miles per hour and are almost perfectly represented over the whole range by the calculated values. However, the equation indicates that the cups continue to run at very low velocities, whereas it is definitely known they stand motionless in light winds under 10 miles per hour. The friction term then ceases to indicate the wind just adequate to keep the cups turning, and its presence in the equation serves the useful purpose of analytically helping the equation to fit the observational data more closely.

Omitting at this time further discussion of the hyperbolic equation, attention is asked to the best way, the only way I believe, of showing in a striking, graphic way, the real curvature and other characteristics of test data. This result is easily attained by plotting the difference-values, $V-W$, against W as shown in figure 3, still not drawn to scale.

In diagrams of $V-W$ plotted against W, the scale for $V-W$ can be chosen so as to bring out clearly not only the conflicts and inconsistencies in the observations but also the inherent curvature which we seek to evaluate. Only by the aid of diagrams like figure 3 can the real characteristics of test data be adequately visualized.

Values of V from test data become possible only after some value has been assigned to the gear train number A, as already explained in connection with equation 1.

I cannot overemphasize the fact that, waiving the effects of the inherent curvature in the line representing the anemometer law, the whole question of the magnitude and distribution of the difference values, $V-W$, that is, the discrepancies between the indicated and the true wind velocities, depends entirely upon the choice of A. If the original basic data are made available it is obvious that almost any desired values of V are readily computed from equation 4 at any time and to correspond to any desired value of A.

Effects of turbulence and beads.—Modern wind-tunnel tests now show that some account must be taken of the aerodynamic effects of so-called fine grained turbulence in the wind stream. This word has come to mean rapid variations of wind speed generally at the rate of 10 or more a second. Apparently it is only these rapid, irregular speed fluctuations that produce the effects to be mentioned later and since open-air winds are turbulent in this way, it must be known whether a particular instrument is affected much or little by such turbulence. Small hot-wire anemometers, actuating thermal types of miliammeters, may be used in measuring turbulence, which is then expressed as a ratio of the average fluctuation to the mean speed. On the scale used a turbulence of 1 percent means that the rapid fluctuations are ± 1.4 percent of the mean speed.[3] These effects of turbulence, including those of beads, are shown in figures 4 and 5 and table 1, which depict and give the original test data reported by the Bureau of Standards. Figure 4 represents three series of tests on cup wheel designated no. 21. It was of identical form, dimensions and construction as the standard 4-hemispherical cup wheel of the Weather Bureau, except that edges of the cups were rolled over in spinning so as to form an external so-called bead of a diameter of a little less than one-sixteenth of an inch. A slender brace wire securely attached to the extremities of the arms was stretched around the periphery of the cup wheel to strengthen it in high winds. Tests by Dr. H. L. Dryden, of the Bureau of Standards definitely indicated that the performance was not affected appreciably by this brace. Without the bead, this cup wheel by the Fergusson tests of 1922 should make fully 686 turns per mile at superhurricane wind velocities. With the bead this number was reduced to 584. By the choice of a gear

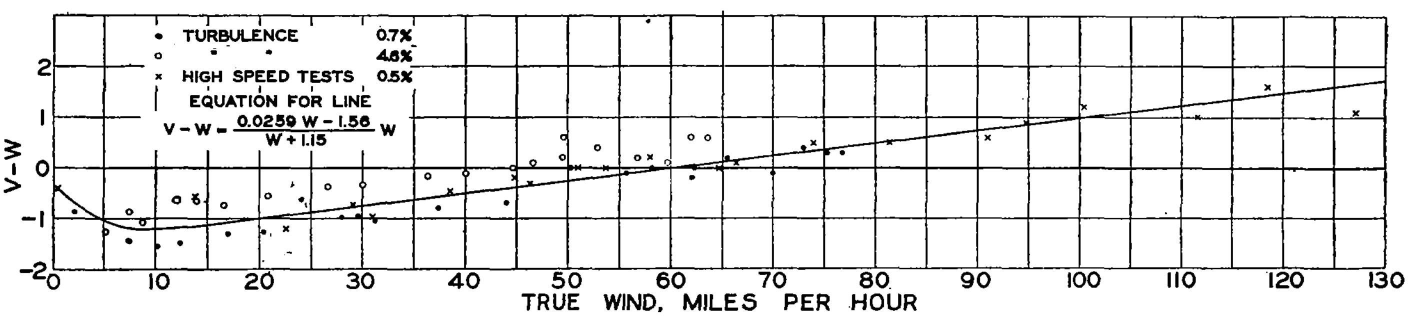


FIGURE 4.—Diagram to scale of values of $V-W$ for a new form of 4-hemispherical cup wheel with beaded edges, recently tested at the Bureau of Standards up to 130 miles per hour. The scale errors are just within 1 mile per hour at all velocities from 0 to 100 miles per hour true wind.

[3] H. L. Dryden, Turbulence, Companion of Reynolds Number. Jour. Aeronautical Sciences, vol. 1, no. 2, April 1934, pp. 67-75.

system of 570 cup turns to the indicated mile, the scale errors of this instrument fall within 1 mile per hour between 0 and 100 miles an hour.

Three pairs of tests on three identical cup wheels are shown in figure 5. The wheels are designated nos. 23, 24, and 25 in table 1, and, for brevity, 1, 2, 3 in the diagram. The cups were 90° cones with the apex bluntly rounded over. Cup wheel no. 24 is the one shown on the instrument in the halftone, (frontispiece). The arms were all 6.5 inches from axis to center of open face of the cups. The cup diameters were all nominally 4.25

(4) The overrun caused by increased turbulence is much less with beaded cups than with smooth cups.

(5) Small variations in size of beads seem to be of secondary importance in cup performance.

While the body of data now available is as yet insufficient to provide final quantitative relationships, nevertheless on the basis of data we have the percentage relationships may be stated about as follows:

(6) The percentage overrun effects due to increased turbulence is higher for high velocities than for moderate and low velocities.

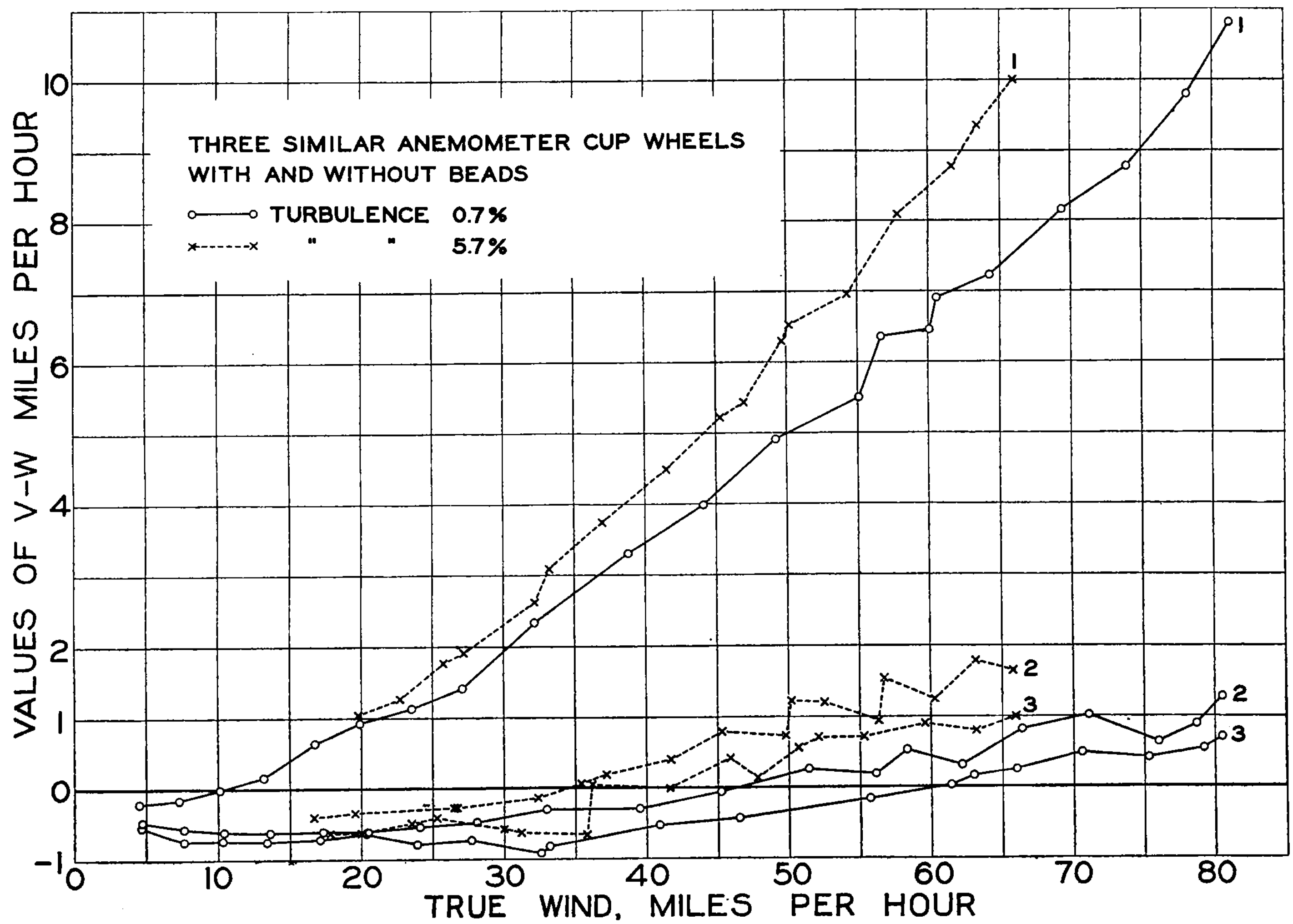


FIGURE 5.—Graphic representation of six test runs in pairs on three 4 cone cup wheels of like dimensions except that no. 1 had smooth surfaces without beads. No. 2 had external beaded edges about one-sixteenth inch in diameter. No. 3 had external beaded edges about one-eighth inch in diameter. Dotted lines are tests with turbulence 5.7 percent. Full lines are with turbulence 0.7 percent.

inches. No. 23 was smooth and without bead. The bead on no. 24 measured about one-sixteenth inch; that on no. 25 was almost one-eighth inch in diameter.

Lack of space at this time prevents any long discussion of this new question. However, we may say categorically:

(1) That cup forms seem to run faster in a turbulent than in a nonturbulent wind stream.

(2) The overrun is much greater for cups with smooth external surfaces. This is especially true of smooth hemispherical cups such as all the old 3- and 4-cup standard wheels.

(3) Cone-shaped cups, especially when provided with external beads, seem to run more slowly than the hemispherical forms.

(7) The percentage overrun on a 4 cone cup wheel without beads, at velocity of about 20 miles per hour, was about 3 percent when the rapid changes of wind speed were about 8 percent of the mean speed.

(8) The overrun was only 1 percent for these same cups with beads a little over one-sixteenth inch diameter.

(9) The run of the old standard nonbeaded cups was more than 17 percent greater than that of the same cups with a comparatively small bead.

(10) Dr. Dryden, of the Bureau of Standards, made the crucial tests on an old standard hemisephrical 4-cup rotor which indicated unequivocally that the marked change in rate that had been noticed in beaded cone and hemispherical cups was due to the bead rather than to the cup form.

(11) Cone-shaped cups seem to possess advantages for standard anemometers over hemispherical cups, but additional tests are needed to evaluate important secondary effects.

Table 1.—*Original test data on anemometer cup wheels nos 21, 23, 24, and 25, as reported by the Bureau of Standards in letters dated Sept. 22, 1933, Jan. 21 and Apr. 12, 1934*

4 CONE CUP WHEEL NO. 23, WITHOUT BEAD

Turbulence, 0.7 percent				Turbulence, 5.7 percent			
True wind speed, miles per hour	Number of contacts counted	Time, seconds	Turns per mile	True wind speed, miles per hour	Number of contacts counted	Time, seconds	Turns per mile
4.46	1	113.0	458	19.75	5	115.4	505
7.32	2	134.0	470	22.73	6	120.0	507
10.07	2	95.4	480	27.15	7	115.6	514
13.20	3	107.8	486	32.25	8	109.8	520
16.78	4	110.2	498	36.95	10	118.2	527
19.91	5	115.2	502	41.5	11	114.8	532
23.48	6	117.0	504	45.3	12	114.0	536
27.10	7	117.8	505	47.0	13	119.0	537
32.20	8	111.2	515	49.7	14	120.0	541
38.80	10	114.0	521	54.3	16	125.4	542
44.1	12	119.8	523	57.9	16	116.4	547
49.2	14	124.2	528	61.7	17	115.8	548
55.1	15	118.8	528	66.0	19	120.0	553
56.7	15	114.2	534	63.5	18	118.6	551
60.1	17	122.6	532	50.2	13	110.0	543
64.3	18	120.8	534	33.15	9	119.2	525
69.4	19	117.6	537	25.77	7	122.0	514
74.0	20	116.0	537				
78.2	22	120.0	540				
81.2	23	120.0	544				
60.6	18	128.0	535				

4 CONE CUP WHEEL NO. 24, MEDIUM BEAD

4.70	1	113.4	432	16.68	4	118.0	468
7.62	2	136.2	444	19.60	5	124.6	472
10.39	2	98.2	452	26.50	6	109.8	475
13.56	3	111.2	459	32.35	8	119.2	478
17.32	4	114.8	464	37.25	10	128.2	483
20.50	5	120.6	466	41.7	10	114.0	484
24.07	6	122.4	469	45.3	12	125.0	488
28.07	7	121.8	471	49.8	12	114.0	487
32.95	8	117.6	471	52.5	13	116.2	491
39.5	10	122.4	477	56.3	15	125.8	488
45.2	12	127.6	480	60.3	15	117.0	491
51.4	13	120.8	483	63.2	16	118.2	494
56.1	14	119.4	482	65.8	17	121.0	492
62.2	16	123.0	482	56.7	14	115.4	493
66.4	17	121.4	486	50.2	12	112.0	492
71.1	18	119.8	487	35.35	9	122.0	481
76.0	19	119.0	484	26.66	7	127.4	475
80.5	20	117.4	488				
78.7	20	120.6	486				
58.3	15	122.4	484				

4 CONE CUP WHEEL NO. 25, LARGE BEAD ABOUT ⅛ INCH

4.71	1	115.0	426	17.78	4	111.8	463
7.62	1	69.8	433	19.97	5	124.0	465
10.34	2	100.0	446	25.30	6	115.8	472
13.45	3	113.2	454	31.17	7	110.0	471
17.10	4	117.2	460	35.75	8	109.4	472
20.27	5	122.2	465	41.6	10	115.4	480
23.90	6	124.6	465	45.9	11	114.0	484
27.70	7	124.6	467	47.8	12	120.2	482
33.20	8	118.6	468	50.7	12	112.4	485
40.9	9	107.0	474	55.3	14	120.0	486
46.5	12	125.0	476	59.6	15	119.0	488
55.7	14	121.0	479	63.2	16	120.0	487

Table 1.—*Original test data on anemometer cup wheels nos. 21, 23, 24, and 25, as reported by the Bureau of Standards in letters dated Sept. 22, 1933, Jan. 21 and Apr. 12, 1934*—Continued

4 CONE CUP WHEEL NO. 25, LARGE BEAD ABOUT ⅛ INCH—Contd.

Turbulence, 0.7 percent				Turbulence, 5.7 percent			
True wind speed, miles per hour	Number of contacts counted	Time, seconds	Turns per mile	True wind speed, miles per hour	Number of contacts counted	Time, seconds	Turns per mile
61.4	15	117.2	481	66.0	17	121.8	487
66.0	17	123.2	482	52.1	13	118.2	487
70.6	17	114.8	483	36.25	9	119.0	481
75.3	20	126.8	483	30.02	8	130.4	471
79.2	20	120.4	483	23.53	5	104.2	470
80.5	20	118.2	485				
63.0	16	121.6	482				
32.60	8	121.2	467				

In all cases 1 contact, C, represents 64 cup-wheel turns = n. Cup wheels 23, 24, and 25 were tested in 54-inch wind tunnel. The arms of each were 6.5 inches from axis to center of cup.

OLD STANDARD 4-HEMISPHERICAL CUP WHEEL NO. 21, WITH SMALL BEADED EDGES AND PERIPHERAL BRACE WIRE

Tested in 54-inch wind tunnel—Turbulence 0.7 percent				Tested in 54-inch wind tunnel—Turbulence 4.6 percent			
2.07	1	319.2	349	5.17	1	106.0	421
7.45	2	134.6	460	7.50	1	61.0	503
10.23	3	139.8	483	8.85	2	104.0	501
12.41	3	111.0	502	11.36	3	113.8	534
17.02	5	128.6	526	14.05	4	121.4	540
20.36	6	126.4	537	16.60	6	152.8	545
24.12	7	123.0	544	20.82	6	119.6	555
28.00	8	119.6	550	30.00	9	122.6	564
31.15	9	121.0	550	36.34	11	122.6	569
37.43	11	121.4	558	40.0	12	121.6	569
44.0	13	121.0	564	44.6	14	126.8	570
50.3	15	120.6	570	46.6	15	130.0	571
55.7	17	123.6	569	49.5	17	138.4	572
58.2	18	125.0	570	52.9	16	121.4	574
62.1	19	124.0	569	56.8	18	127.6	573
65.5	21	129.2	572	59.7	19	128.4	571
70.0	22	126.8	571	62.0	19	122.8	574
73.0	22	121.2	573	63.6	19	119.6	576
76.8	23	120.6	573	49.6	15	121.0	577
75.3	22	117.6	573	26.59	8	123.4	562
62.3	19	123.2	570				
29.56	9	127.0	552				

Tested in 36-inch wind tunnel—Turbulence 0.5 percent							
13.8	3	98.7	506				
22.5	6	113.5	540				
29.0	8	114.4	554				
30.9	9	121.3	552				
38.4	11	117.0	564				
44.7	14	127.0	568				
46.3	14	123.0	566				
51.0	16	126.9	570				
53.7	16	120.4	571				
58.0	18	125.0	572				
64.7	20	125.0	570				
66.4	20	121.6	571				
74.0	23	124.8	574				
81.4	25	123.4	574				
91.0	28	123.6	574				
94.8	29	122.5	576				
100.5	31	123.2	577				
111.6	35	125.6	575				
118.5	18	60.6	578				
127.2	20	63.0	576				